MIMIC : Mobile Mapping Point Density Calculator

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ABSTRACT

The current generation of Mobile Mapping Systems (MMSs) capture increasingly larger amounts of data in a short time frame. Due to the relative novelty of this technology there is no concrete understanding of the point density that different hardware configurations and operating parameters will exhibit on objects at specific distances. Depending on the project requirements, obtaining the required point density impacts on survey time, processing time, data storage and is the underlying limit of automated algorithms. A limited understanding of the capabilities of these systems means that defining point density in project specifications is a complicated process. We are in the process of developing a method for determining the quantitative resolution of point clouds collected by a MMS with respect to known objects at specified distances. We have previously demonstrated the capabilities of our system for calculating point spacing, profile angle and profile spacing individually. Each of these elements are a major factor in calculating point density on arbitrary objects, such as road signs, poles or buildings - all important features in asset management surveys. This paper will introduce the current version of the MobIle Mapping point densIty Calculator (MIMIC), MIMIC's visualisation module and finally discuss the methods employed to validate our work.

Categories and Subject Descriptors

I.6 [**Computing methodologies**]: Simulation and Modelling; B.8 [**Hardware**]: Performance and Reliability

General Terms

Algorithms, Experimentation, Performance

Keywords

LiDAR, mobile mapping, point density

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1. INTRODUCTION

This paper details the design and development of MIMIC - a system for calculating the point density on the road surface and on roadside infrastructure captured by laser scanners mounted on specific types of MMS. This paper will display the recent advances that have built on our previous work.

1.1 Resolution

The primary focus of the research community to date has been on developing automated or semi-automated algorithms for processing the large point clouds captured by modern terrestrial or mobile mapping systems [2, 9, 15, 18, 19]. Consequently, assessing the performance of these systems has been overlooked. When performance was assessed, it was generally restricted to accuracy tests on specific systems [1, 8] and no research exists assessing the performance of generic MMSs. Improving the body of knowledge in this area is important as one of the fundamental questions facing research groups working with extraction algorithms is what point density to expect for objects at different ranges. An object with insufficient laser returns will not be recognised no matter how efficient the algorithm and from the various automation algorithms employed in [12] we can see that point density directly impacts on the accuracy of the resulting model. Cylindrical objects such as telegraph poles or sign posts also need a minimum number of points from each scan line to hit the target to reliably recognise a circular shape. For example, work by [14] and [16] require a minimum number of profiles on post objects for them to be detected. MMSs are new to the market and to date there has been no concerted effort to assess their combined capabilities. This paper will focus solely on MMSs equipped with one or more 2D circular laser scanners.

One of the main decisions facing a manufacturer when designing a laser based mobile mapping system is the number, location and orientation of the scanners on the vehicle. Although there have been tests investigating the best scanner configuration to minimise occlusions [21], no research has been carried out to find the optimal location for a single scanner (i.e. rear, side, front) that will provide the highest point density, or the optimum orientation for the scanner. The MMS designed at the National Centre for Geocomputation (NCG) is a single scanner system, so we aim to provide a definitive view of its capabilities which we anticipate will then be of use to similar systems but also to those operating more than one scanner. The orientation of the scanner is important. Scan lines cannot be perpendicular to the direc-

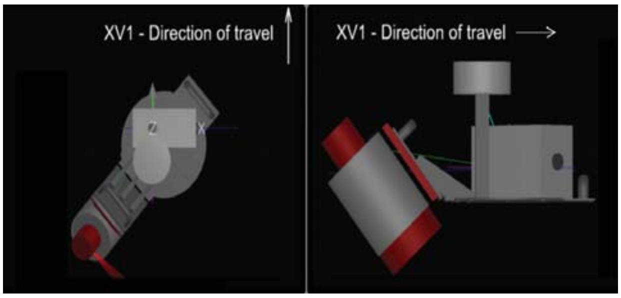

Figure 1: Dual axis scanner rotations

tion of travel or they will not intersect with structures whose sides are also perpendicular to it. By rotating the scanner in the horizontal plane, this issue can be resolved. A vertical rotation of the scanner deals with structures above the vehicle which might otherwise be missed such as overhead road signs or bridge faces. We hope to define what the optimum horizontal and vertical orientations are when surveying for particular features. A dual axis scanner rotation (a vertical and a horizontal rotation) can be seen in Figure 1.

A major benefit of using MMSs for surveys is that they are capable of operating at highway speeds. The trade-off when operating at higher speeds is that point density decreases as vehicle velocity increases and in certain circumstances this necessitates multiple passes to ensure a dense point cloud (multiple passes are also employed to ensure all sides of an object are captured) that will meet project specifications. One of the goals of the MIMIC system is to define the maximum speed for specific scanner configurations that will provide the required point density and therefore define the minimum number of passes required. This should result in a reduced survey time, a reduced processing time and also a reduced file size as in practice the point density side of the mission planning stage is still largely left to interpretation by experienced operators.

1.2 Mission Planning

The current method for ensuring that a mobile mapping survey meets the required point density is to overcompensate with scan hardware or to drive the route multiple times, a practice that can result in more data being captured than necessary. This also results in increased processing time and requires increased storage space. Another popular method to ensure a high point density is for surveys to be carried out at a lower speed than is necessary [6, 7], which can impact on the productivity of a MMS. A third method is mission planning, although a number of factors must be taken into account to do this correctly. Firstly, scanner rotations must be incorporated. Secondly, target rotations must be incorporated. Thirdly a decision must be made whether to provide the user with the point density information for the whole object, or limit it to the point density per m^2 calculated from one centre point only. This can introduce errors for angled surfaces. Finally, it must allow for objects that are elevated above or below the scanner and to-date, nothing caters for all of these factors. Our aim is to incorporate each of these elements.

1.3 Work to date

Certain initial studies have produced interesting results in the area of point density acquired by mobile mapping systems. Both [10] and [13] supplied results of profile spacing at certain mirror speeds and vehicle velocities, however as this was a qualitative post-mission measurement process it has no facility for quantitatively calculating the result pre-mission. One of the improvements implemented in MIMIC was to create an algorithm that will work for any scanner configuration, any vehicle velocity and will also incorporate scanner and target orientation into the system. This is something that has been lacking in studies to date. In their work on theoretic point density [11] have highlighted the effect a change in vehicle direction and velocity has on scan lines. A recent study [20] testing the metrology specifications of terrestrial laser scanners (TLS) shows how current this issue still is, and as TLS is a more mature technology than MMSs and has a different scan geometry due to the fixed nature of the scanner also shows the need for such a study to be carried out on MMSs. In an early version of our system [3] we designed a method for calculating the profile spacing for a MMS on planar, orthogonal surfaces with a single axis scanner rotation (horizontal or vertical only), varying mirror frequencies and vehicle velocity. We have also qualitatively defined [4] the angular change caused by dual axis scanner rotations on perfectly vertical planar surfaces and a quantitative method for calculating point spacing on profiles for different systems on planar surfaces at different ranges. In [5] the effect that a dual-axis scanner rotation has on the profile angle was investigated and work to design a theoretical system to calculate the angular change on profiles exhibited on horizontal and vertical surfaces for different system configurations was carried out. The second goal of the research presented in [5] was to include in our algorithm a method for incorporating surfaces that were not parallel to the direction of travel or that were not perfectly vertical, such as walls facing away from the road or sloped surfaces. As subsequent improvements were included into the system, culminating in MIMIC, the hypotheses and calculations involved were tested against real-world data captured with the MMS designed at the NCG and have been validated at each stage. We will now discuss MMSs and the MMS designed and built at the NCG in greater detail.

2. MOBILE MAPPING SYSTEMS

Mobile mapping systems enable high density spatial data to be collected along route networks. By combining hardware such as high accuracy GNSS/INS, laser scanners and imaging sensors on-board a moving platform enables surveys to be carried out rapidly and in a cost effective manner [8]. These data can then be utilised in a number of ways, such as route safety audits, road authorities GIS, infrastructure surveys and change detection for national mapping agencies. Land based MMSs outperform aerial systems in a number of ways. They exhibit a higher point density, better vertical accuracy, large scale information such as road sign detail or detailed infrastructure condition can be recorded and these systems can capture features that are sometimes obscured from aerial platforms [1]. In contrast to TLS surveys, extensive ground control is not essential. The MMS at the NCG is representative of the state of the art in the mobile mapping field.

Figure 2: XP1 Mobile Mapping System

2.1 XP1 MMS

The multi-disciplinary research group StratAG, established to research advanced geotechnologies at NUI Maynooth have completed design and development of a multi-purpose land based Mobile Mapping System (XP-1). The primary components of the XP-1 (Figure 2) are an IXSEA LANDINS GPS/INS, a Riegl VQ-250 300KHz laser scanner and an imaging system consisting of up to six progressive-scan cameras. Imaging sensors include a FLIR thermal (un-cooled) SC-660 camera and an innovative 5-CCD multi-spectral camera capable of sensing across blue, green, red and two infrared bandwidths. Even with a single Riegl VQ-250, the XP1 is capable of capturing dense point clouds quickly and efficiently.

2.2 Laser Point Clouds

Laser scanners are capable of capturing hundreds of thousands of points per second. The XP1 is equipped with a single Riegl VQ-250 scanner that is capable of emitting up to 300,000 pulses per second. Commercial systems like Riegl's VMX250 operate dual scanners (2 x VQ-250), which are therefore capable of capturing up to 600,000 points per second. Their latest dual scanner system, the VMX450 (2 x VQ-450) is capable of emitting upwards of one million pulses per second. After being captured, each of these points is an individual georeferenced piece of data and when viewed in conjunction with the other points comprise a 'cloud', giving the name 'point cloud'. Figure 3 displays a sample point cloud captured by the XP1 system. The point cloud collected by a MMS like the XP1 exhibits three very distinctive features. These are profile spacing, profile angle and point spacing and they constitute the primary variables involved in the point density calculation. We will now investigate scan profiles and points in more detail.

2.2.1 Profiles

For the current generation of MMS, when a 2D circular laser scanner is mounted on-board, the forward motion of the MMS creates gaps between scan profiles (or scan lines) for each mirror rotation. Rotations of the scanner or target in the horizontal or vertical plane change the angle that these profiles intersect with horizontal and vertical surfaces, termed the 'profile angle'. This alters the number of profiles hitting a target, the spacing between profiles and ultimately the point density. Examples of profile spacing and profile angle can be seen under outputs in Figure 5. Our system has been proven to successfully calculate both profile spacing and profile angle [3], [5]. These are important factors in

Figure 3: An example of a MMS Point Cloud

quantitatively calculating the profile information and hence the point density for arbitrary objects. Figure 4 illustrates the importance of profile angle for a vertical surface. Without a vertical rotation of the scanner narrow vertical surfaces are not captured sufficiently to resolve their shape and dimensions accurately from the point cloud. However, by introducing subsequent 15 degree increments in the vertical rotation of the scanner the number of points hitting the target is increased. To date, the optimum scanner rotation for targets of different dimensions has not been identified and determining this is one of the goals of our research. Profile spacing and profile angle are a combination of a number of factors. The vehicle speed, the rotation of the scanner, the scanner mirror speed (how many rotations per second) and the rotation of the object all influence profiles. Table 1 details all of the attributes impacting on profile spacing and profile angle that have been included in the MIMIC system.

2.2.2 Points

The distance between subsequent points along a profile is known as the point spacing. Point spacing along a profile line is illustrated under outputs in Figure 5. As MIMIC is designed to identify the theoretical point density - i.e. what pulses should return from an object, we therefore assume a return from every pulse, one return only per pulse and also a smooth surface. In practice this will not always be the case, but the majority of man-made roadside infrastructure is smooth and will therefore provide a return for each pulse. Additionally, the short measurement range between the scanner and the roadside features ($< 20m$, while the maximum scan range for the VQ-250 when operating at $300KHz$ is $200m$) ensure a strong return. Point spacing is influenced by a number of factors, such as the angular resolution of the scanner, the pulse repetition rate, the range to the target, the orientation of the target, and the orientation of the scanner. Our system has been designed to calculate the point spacing incorporating each of these [4]. Table 1 details all of the attributes impacting on point spacing that have been included in the MIMIC system.

2.2.3 Point Density

These three elements - profile spacing, profile angle and point spacing constitute the primary variables involved in the point density calculation. Point density is the number of points per square unit of measure. Point density per m^2 is

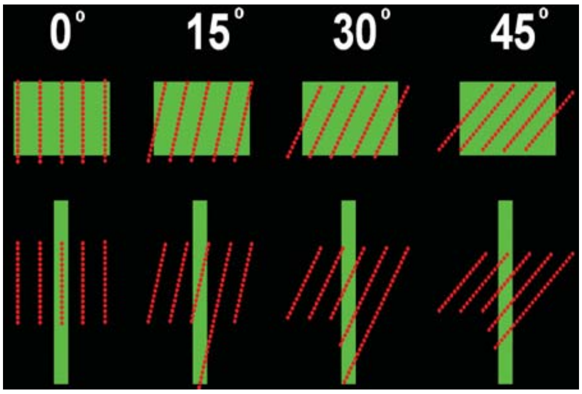

Figure 4: Profile Angle

Table 1: Calculation Module Attributes

Attribute	Class	Impacts on
Vehicle Speed	Vehicle	Profile Spacing
Yaw	Vehicle	Profile/Point Spacing
Roll	Vehicle	Profile/Point Spacing
Pitch	Vehicle	Profile/Point Spacing
Field Of View	Scanner	Profile/Point Spacing
Horizontal Rotation	Scanner	Profile/Point Spacing
Vertical Rotation	Scanner	Profile/Point Spacing
Pulse Repetition Rate	Scanner	Point Spacing
Mirror Rotation Speed	Scanner	Profile Spacing
Number Of Scanners	Scanner	Point Density
Scanner Elevation	Scanner	Point Spacing
Second Scanner Offset	Scanner	Point Spacing
Horizontal Rotation	Target	Profile/Point Spacing
Vertical Rotation	Target	Point Spacing
Range	Target	Point Spacing
Base Elevation	Target	Point Spacing
Height	Target	Point Spacing

an unsuitable metric for a large amount of roadside features as they are non-planar, complex objects whose dimensions are non regular. In our work we aim to combine each of the features and have developed a new, innovative method for displaying point density for different types of roadside infrastructure.

3. MIMIC ARCHITECTURE

This section will describe the latest version of the MIMIC system and its component modules. In Figure 5 we display the workflow of MIMIC. MIMIC consists of two modules. The first module carries out the calculation of profile angle, profile spacing and point spacing. The second module is the visualisation module that displays the results for the user. The calculation module requires user input of system variables.

3.1 Input

MIMIC requires a set of user specified information. This must detail the scanner hardware, vehicle behaviour and target type and dimensions. Table 1 displays each of the attributes impacting on point spacing that have been included in the system. The first input variable is the vehicle class.

3.1.1 Vehicle

To properly define the behaviour of a MMS the vehicle must be assigned a number of attributes. The first of these is the vehicle speed and for ease of reference is input in km/h. This is then converted into m/s and is one of the major factors impacting on profile spacing. The next variable, yaw, is used to simulate any course deviation during the measurement, or curved roads. The final two variables, pitch and roll are used to simulate the road slope and camber respectively. The next input element required for the calculation is the scanner.

3.1.2 Scanner

The MIMIC system has been designed to function with any of the current generation of 2D circular scanners. To facilitate this the scanner class has also been assigned a number of attributes. MIMIC has been designed to incorporate horizontal and vertical rotations of the scanner. Each scanner also has an angular resolution, which is the angular change between subsequent laser pulses. This is dependent on the scanners capability but also the field of view of the scanner. For a full 360° rotation the angular resolution is found by dividing 360° by the number of pulses per mirror rotation. To accommodate dual scanner systems like the VMX-450, the number of scanners must also be specified. The position of the second scanner on the vehicle and its elevation must also be specified by the user for range calculations. The scanner variables must be specified for each extra scanner on the MMS. Following this, information on the environment and target are required.

3.1.3 Target

MIMIC can handle a number of different types of target. To simplify the calculation process, we first create a set of grids on the object. The user is required to specify the number at the input stage. The grids will be discussed further in section 3.2.1. Targets can be planar or cylindrical. Cylindrical targets are broken down into a series of planar grids. Targets can be vertical structures such as walls and buildings, flat surfaces representing the road underneath the vehicle, angled vertical structures representing banked surfaces, tall narrow objects representing signs and cylindrical objects representing poles. Each target has different attributes. A horizontal and vertical rotation allows for representation of angled surfaces. Horizontal range to the target from the scanner must also be specified. Once the offset to the second scanner has been defined in the scanner class, the range to the second scanner is then found. The targets base elevation must be specified and also the height of the target off the ground. Once each input variable has been entered the calculation process begins.

3.2 Calculation

The calculation module requires all of the input data and through a combination of geometrical formula and 3D surface normals we calculate the number and distribution of laser returns from an object. The methods employed to date have been well documented in [3], [4] and [5]. We will now demonstrate two improvements to these methods that will ultimately allow us to calculate point density. The first of these is the grid approach.

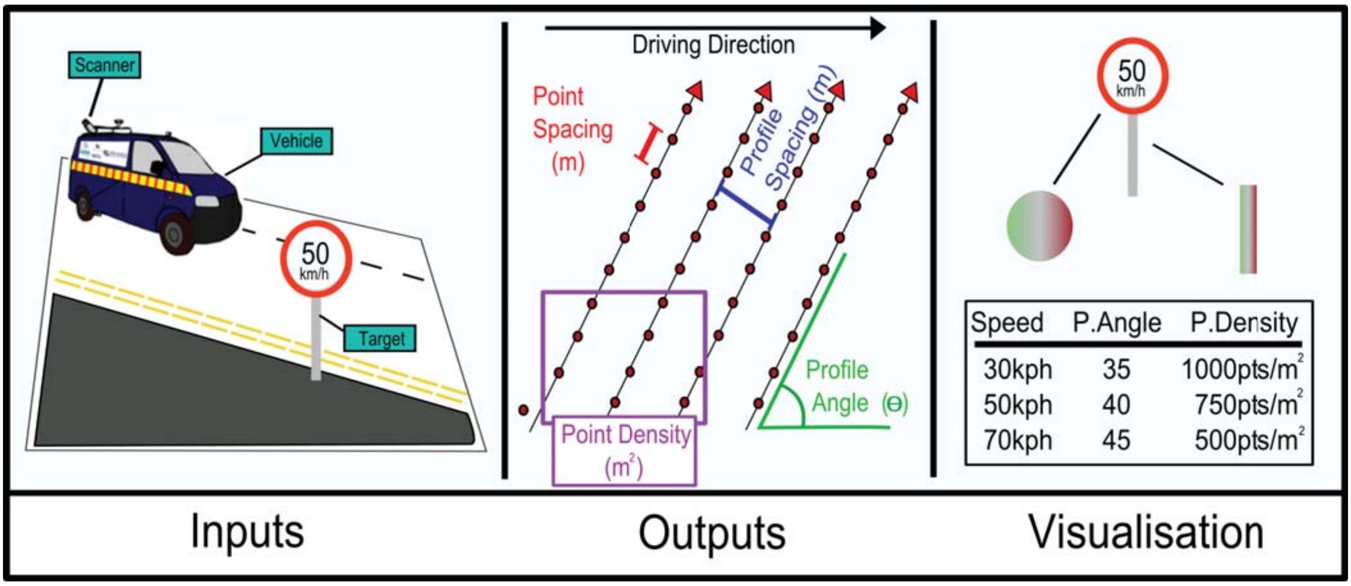

Figure 5: System Workflow - inputs, outputs and visualisation.

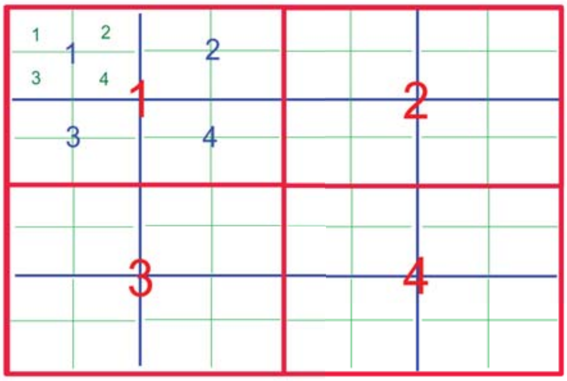

Figure 6: Gridding a region

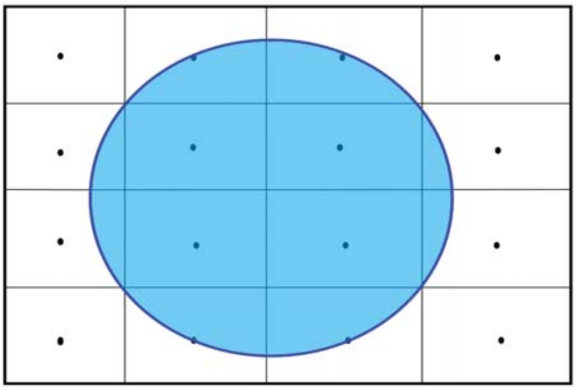

Figure 7: Gridded bounding box fitted over circular target.

3.2.1 Grids

The point density for each surface is calculated by dividing it up into a number of grids. This is displayed in Figure 6. The number of grids is user-specified when defining the target (Section 3.1.3). The user can request that each grid in a simple four box grid can be quartered to 16 grids, or quartered again to 64. This increases the number of measurements but also the accuracy of the final result. Increasing the number of grids is dependant on several factors, such as target size, range and rotation. The profile angle, profile spacing and point spacing are then calculated for each grid. Although this method has the advantage of speeding up and simplifying the calculation process, it is therefore not as accurate as calculating the point spacing for each point individually. The optimum number of grids necessary to provide an accurate representation of the target while also minimising processing time has not yet been identified and determining this is one of the goals of our research. Our visualisation method has been applied to regular shapes, but can also be applied to more complicated structures with a bounding box approach.

3.2.2 Bounding Box

For more complicated structures, the MIMIC system operates by breaking down an irregular 2D or a 3D object into a series of 2D planar surfaces. A gridded bounding box is then fitted around each planar 2D surface. This allows the number and distribution of laser returns from different objects (e.g. cylinders, circles, hexagons, triangles) to be calculated using a single process. Our next goal is to recombine these planar surfaces to provide a value for point density of the 3D object. Figure 7 displays the gridded bounding box approach being applied to a circular road sign. The advantages of this approach is that standard 2D geometrical formula can be applied. The disadvantage is that care must be taken when recombining the planar surfaces that there is no duplication of points. The MIMIC system compensates for this.

3.3 Output

The output from the three inputs (scanner, vehicle, target) to the calculation module are;

- The profile spacing.
- The point spacing at the specified target locations.
- The profile angle.

These outputs are necessary to calculate the number and distribution of laser returns from an object. Figure 5 (outputs) illustrates these. Although correct, the data is not in an easily understandable format for the user at this stage and must be visualised differently. We will now discuss the visualisation component of MIMIC.

3.4 Visualisation Module

Once the calculations have been performed, the visualisation module is designed to combine the information on profile angle, profile spacing and point spacing to the user in a clear and easily understandable format. To minimise clutter and improve understanding of the results the different output data cannot be displayed simultaneously and therefore different display methods have been designed for each output.

3.4.1 Point Density

We are currently in the process of combining all of the outputs to calculate point density. Once calculated, it must then be visualised. One option for visualising point density that we are currently investigating is to apply multivariate interpolation, specifically inverse distance weighting (IDW) displaying areas of lowest to highest point spacing. The point spacing at the centre of each grid is calculated, and then using IDW we interpolate between the known points. Using IDW, the point spacing is displayed in Figure 8 for a target 5m wide x 4m high on a planar surface for a single scanner system at a range of 5m and with the target rotated 30^o in the horizontal plane. We applied 64 grids (8 x 8) and each grid represents a planar surface 0.625m wide x 0.5m high. Alternatively, for a more detailed representation the point spacing at the centre of each grid can be illustrated numerically. In the case of multiple scanners, a different text colour can be applied to differentiate. This method effectively visualises the point information per target, but not the profile spacing or angle although both are included in the point density calculation. The IDW method provides an excellent method for visualising point spacing and this can also be applied to point density once profile information has been applied.

3.4.2 Profiles

Depending on the angle of the surface, the profile angle is different for each scanner and can be represented by lines marked on the target. The lines are separated by the calculated profile spacing using the scanner, target and vehicle input variables. As displayed in Figure 4 profile angle is an important factor when surveying narrow objects so it is important to include this when assessing the capabilities of an MMS configuration and it is an important output of our system. We will now discuss the methods employed for validating our results.

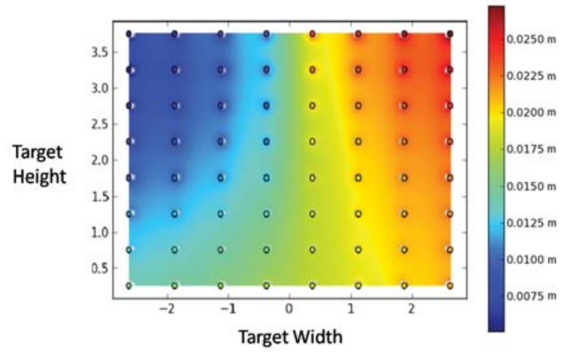

Figure 8: IDW displaying point spacing on an angled surface

4. VALIDATION

Our previous work has documented the methods employed to ensure robust testing of the system. We verify our system using three datasets. The first is a theoretical dataset, designed in a computer aided drawing (CAD) environment (Figure 9). The second is a real world point cloud captured by the XP1 MMS of a test route designed specifically for this research (Figure 10) at NUIM. The third and final test is a real world point cloud captured by our XP1 MMS of existing features, such as signs, walls and buildings surveyed during a project in England (Figure 11). For each dataset we identified a number of suitable sample areas for tests and a series of measurements were taken at each location. For each dataset, the point spacing, profile spacing and profile angle were measured.

4.1 CAD Tests

For our initial tests [5], we created a number of planes representing different surfaces and different scanner rotations in a CAD environment (Figure 9). Dataset 1 consisted of fifty tests, constituting five horizontal surface rotations and five vertical surface rotations for five different dual axis scanner rotations. We were then able to manually measure the point spacing and profile angle on each surface for each dual axis scanner rotation in the CAD environment. This method proved to be time consuming as it only works for one mirror rotation. After successful validation of our system outputs against the measurements from the CAD environment we were then required to validate this in a real world setting.

4.2 Test Route

After the successful completion of the CAD tests which verified our theoretical model, the next stage of our testing required us to compare our results with point cloud data captured by our XP1 mobile mapping system on a test route designed specifically for this project. However, as we cannot vary the rotations of our scanner due to a rigid mounting, we had to vary the rotation of the surfaces. The test route consisted of a series of large, planar rectangular targets positioned at regular intervals and ranges along a roadside. Twelve targets were placed along the direction of travel. The targets were parallel, rotated horizontally, angled vertically and also a combination of horizontal and vertical in relation to the vehicle. A portion of the test route is conceptualised

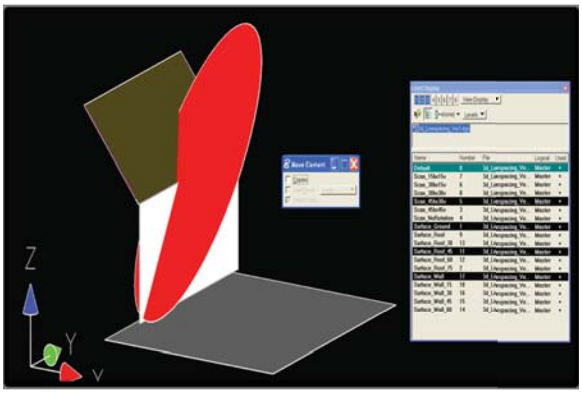

Figure 9: CAD Tests for measuring profile angle

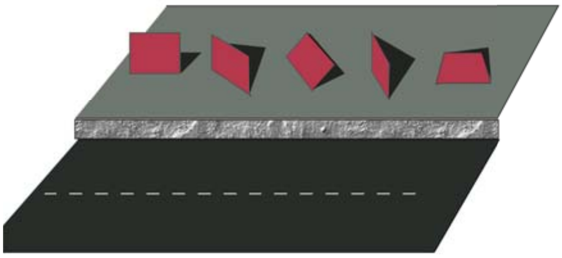

Figure 10: Targets along test-route

in Figure 10. Certain targets were placed at different ranges to test the robustness of the system (not visualised in Figure 10). The parallel targets were chosen for exploring the dual axis rotation effect introduced, while the horizontally rotated and vertically sloped targets were chosen for identifying the effect of angled surfaces on profile angle and for subsequent tests on profile spacing. The targets were placed at different ranges to allow us to estimate this effect on the point spacing on parallel and angled surfaces.

4.3 Existing Features

After the completion of the CAD tests and also the use of data from the test route which in turn verified our theoretical model and then assessed it experimentally we could proceed with the final set of tests. This step required us to compare real world point cloud data captured by our XP1 MMS of real world features and see how our calculations for profile spacing, profile angle and point spacing performed against this test data. We chose man made features such as walls and building faces, and were able to use the 3D point cloud to measure the horizontal and vertical angles of these features. Using software designed by researchers at the NCG [17], we were able to identify and extract areas of interest quickly from very large survey files.

4.4 MIMIC - Results and Discussion

Early versions of our system performed well in both CAD and real-world environments and have been well documented in [3],[4] and [5]. Results representative of the different real world tests of the current version of MIMIC can be seen in Table 2, highlighting the difference between the measured values and our predicted values. Although errors are once again present, they are significantly reduced thanks to the inclusion of vehicle dynamics. As yaw is unlikely to change significantly over the course of ten scan lines (0.1 of a second), once the angle of the wall to the direction of travel has been identified it can be ignored as a factor. Roll and pitch alter the surface normal of the scan plane and this can lead to errors in the profile angle and point spacing calculations. By including vehicle dynamics in the vehicle class they can be compensated for. The different visualisation methods employed effectively display point cloud information to the user.

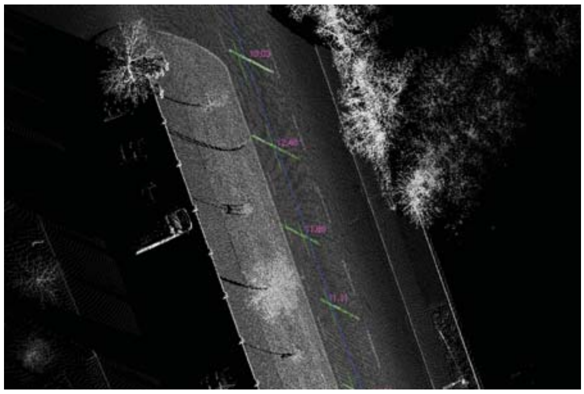

Figure 11: Profile Spacing Measurements

5. CONCLUSION

This study has taken our previous qualitative and quantitative work on predicting profile spacing, profile angle and point spacing for different mobile mapping systems on planar and angled surfaces for dual axis scanner rotations and combined them into a single system, MIMIC. The calculation component has been combined with a visualisation component. We have verified this method theoretically in a CAD environment and then experimentally using two real world datasets, one of a manufactured test route and one of existing features. MIMIC performed well in the CAD environment and errors present in previous real world tests have been identified as resulting from vehicle dynamics and these have now been incorporated into our system. One issue with this method is that this system is being designed to identify point density pre-mission, however roll and pitch will be unknowns at that time and so a minimum point density is likely to be specified for objects on standard road gradients in our future work. It is hoped that this work will provide valuable information on MMS performance that can be used when defining future standards.

6. ACKNOWLEDGEMENTS

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Table 2: System Performance - Prediction errors for single scanner at 45^o horizontal and 45^o vertical

Target	Range	velocity	Target $H\theta$	Target $V\theta$	Prof.Angle error	Prof.Spacing error	Point Spacing error
1	5.2m	4.1(m/s)	0	0	1.63 dec.degrees	0m	0.002m
2	6m	4.31(m/s)	0	15	1.22 dec.degrees	0.001m	0m
3	7.85m	7.71(m/s)	0	30	0.97 dec.degrees	0m	0m
4	6.5m	8.12(m/s)	0	45	1.75 dec.degrees	0m	0.001m
5	6m	7.06(m/s)	17.85	7	1.37 dec.degrees	0.002m	0.002m
6	5.2m	11.82(m/s)	46.5	7	1.89 dec.degrees	0.001m	0.002m
7	5.2m	8.92(m/s)	74	20	2.09 dec.degrees	0m	0.002m

under the National Development Plan.

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